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Research paper

Assessing sugarcane expansion to ethanol production under climate change scenarios in Paranaíba river basin – Brazil

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ABSTRACT

Agroclimatic aptitude can provide information on regions with less impact to the environment for sugarcane growth to ethanol production. In this study, agroclimatic aptitude maps are generated for the region encompassing the Paranaíba river basin in central-western Brazil, which has presented suitable conditions for sugarcane expansion. Considering a rainfed framework, the hydrological requirements were estimated using meteorological station data; numerical integrations of climate change projections, from the Geophysical Fluid Dynamics Laboratory's Earth System Models under two climate change scenarios; and the crop model, CROPWAT 8.0, from the Food and Agriculture Organization of the United Nations. The resulting agroclimatic aptitude maps exhibit areas of sugarcane vulnerability to climate change, as well as potential regions for its expansion. None of the performed analyses indicate the increase in temperature as a limiting factor for sugarcane production in that region. Considering thermal and hydric aptitudes, the water deficit is the only limiting factor in the study area, therefore sugarcane production would require irrigation. This study presents the southwestern region of the river basin as more suitable to the expansion of sugarcane, because the lower risk of water deficit, under different climate paths with distinctive *El Niño* Southern Oscillation variability conditions. Additionally, the southwestern part of the Paranaíba river basin has fewer environmental conservation units, as well as a vast pastureland. Cattle herd can be reallocated toward degraded pasturelands, which in turn can be recovered. Therefore, sugarcane expansion to the southwestern region of the Paranaíba river basin would affect less the environment.

1. Introduction

Environmental protection is a growing matter worldwide, especially in association with global warming and climate change. Thus, several studies assess measures to reduce Greenhouse Gas Emissions (e.g. [1,2], and [3]), and the Working Group III of the Intergovernmental Panel on Climate Change (IPCC)'s report identifies the use of renewable energy (RE) in different sectors as one of the most important mitigating factors of climate change [4].

In that regard, the transport sector plays a crucial role in the world's demand for RE. According to [5] between 2000 and 2015 the world consumption and production of liquid biofuels level raised around 663% and 700%, respectively. Indeed, approximately 75% of the liquid biofuels used in the world are by one type of biofuel: the ethanol [6]. Although Brazil and the USA use distinct types of main feedstock, i.e. sugarcane in Brazil and corn in the USA [7], together they are responsible for 85% of the ethanol world production.

Data from Brazilian governmental agencies [8,9], and [10] show that between 2005 and 2014 the Brazilian manufacturing level of the main liquid biofuels, ethanol and biodiesel, raised by 200%. Historical series from Ref. [8] indicate that between the sugarcane crops of 2005/2006 and 2015/2016 there was an increase in ethanol production of around 11 million m^3, and the cultivated area expanded approximately 28 billion m^2 (2,8 million ha).

The State of São Paulo (SP) is the main sugarcane producer in Brazil [11], mainly due to good climate and soil conditions, technological innovations and available infrastructure. According to [12], however, the increase in land values in SP is pushing sugarcane production to expand towards the central Brazil.

Between the sugarcane crops of 2005/2006 and 2015/2016, the highest rate of sugarcane area expansion occurred in the central-western region of Brazil [13], even though this region has some constraints

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to sugarcane expansion (e.g. lack of infrastructure) [12].

The Decennial Energy Plan [14] projected that, from 2016 to 2026, the ethanol production will grow from approximately 29 million m^3 to 44 million m^3, with sugarcane cultivated area growing from approximately 90 billion m^2 (9,0 million ha) to 98 billion m^2 (9,8 million ha).

The increase in the world's demand for ethanol leads to the expansion of sugarcane cultivated area, with potential impacts on food and water availability, in addition to the possible risk to environmental conservation units.

This research addresses the problematic of the increase in ethanol production and, consequently, the expansion of sugarcane cultivated area, with implications to water and land use, food security and threats to environmental conservation units. In that respect, Agroecological Sugarcane Zoning (hereafter AEZ-Cane) is a methodology that provides strategic tools, such as climatic, edaphoclimatic and pedologic aptitudes and, along with information on land use, has proven to be useful to guide stakeholders in the formulation of policies to regulate the expansion of the sugarcane cultivated area with less impact to the environment [15].

Thus, the primary goal of this research is to apply part of AEZ-Cane methodology to determine the agroclimatic aptitude for sugarcane over the Paranaíba river basin (hereafter PRB), which is considered one of the main sugarcane expansion areas of Brazil. For this, weather station data, two IPCC models of the Coupled Model Intercomparison Project Phase 5 (henceforth IPCC-CMIP5), and the computer program CROPWAT 8.0 were used.

The purpose is to find suitable directions for crop expansion regarding land uses and potential threats to environmental conservation units, such as those located in Pantanal, a savanna wetland biome and one of the largest wetland territories in the world [16]. Results from this study might be relevant to agriculture planning strategies to mitigate environmental impacts, accounting for uncertainties associated with a changing climate.

2. Materials and methods

The methodology employed in this study is based on the AEZ-Cane method, i.e., verifying the sugarcane agroclimatic aptitude through thermal and hydric maps. The creation of these maps was accomplished with meteorological station data, results from two IPCC–CMIP5's Earth System Models (hereafter ESMs), and CROPWAT 8.0, a software designed to calculate crop water and irrigation requirements, from the Food and Agriculture Organization (FAO) of the United Nations [17].

The results from CROPWAT 8.0 and the annual mean near-surface air temperature were spatially interpolated using Cressman Objective Analysis [18], available on [19]. Additionally, possible areas of expansion toward the environmental conservation units were checked for, as well as the land use data of the region.

2.1. The study area

The PRB was chosen since it has station data availability, policies for energy production, and it is relevant as a sugarcane expansion area due to sugarcane growing production [13,14] [20], and [21].

The study area, delimited by 13–23°S and 45–55°W, was selected to be larger than the limits of PRB to increase the available station data (Fig. 1). It has approximately 600 billion m^2 (60 million ha), and includes PRB, which corresponds to 222.6 billion m^2 (22.26 million ha) [22,23], and [24].

PRB is the second largest of the six hydrologic units that integrated the Paraná Hydrographic Region, occupying 25.4% of the entire region [22] and [23], and encompasses, in part, the following states: Goiás [GO] (63.27% of the total area), Minas Gerais [MG] (31.67%), Distrito Federal [DF] (1.65%) and Mato Grosso do Sul [MS] (3.41%). According to [25], the pastureland in PRB is approximately 78 billion m^2 (7,8 million ha). The PRB has 49 sugar and ethanol plants, mainly located in the western side of the river basin [26].

The predominant climate in PRB is "Aw", i.e. tropical climate with a dry winter [27]. Further studies [28] and [29] have also confirmed "Aw" as the currently prevalent climate type in this watershed.

The *Cerrado* biome prevails in PRB, and is one of Earth's biodiversity hotspots, with the richest savanna in the world. It has several types of vegetation, which can be divided into three categories: grassland, forestland and shrubland [30-32].

2.2. Datasets

The data used in this work are categorized as follows: meteorological, soil properties and crop type.

2.2.1. Weather station data

The meteorological variables are mean, minimum and maximum near-surface air temperatures [K], air relative humidity [%], precipitation [mm], wind velocity [m/s] and sunshine duration [s]. The meteorological station data applied in this study are the climatological standard normals from the National Institute of Meteorology (INMET) [33] in Brazil. These data were analyzed and consisted by specialists from INMET, following the procedures recommended by the World Meteorological Organization (WMO) [34,35].

The meteorological data used are comprised of monthly averages of daily observations from January 1961 to December 1990, for each of the eighteen station sites shown in Fig. 1. This period is one of the standard periods in climate assessments [36], and widely used in climate projections [37,38].

2.2.2. Soil properties data

The PRB has three predominant types of soil: Oxisols, Inceptsols and Utisols, covering 63%, 18% and 10% of the basin, respectively [25], [39]. As there are several types of soil and agricultural management in the basin area, the chosen soil properties were the ones which could represent the prevailing soils [40-42]. In this case, they were the soil properties of the red sandy loam textural class [39].

2.2.3. Crop data

Sugarcane is a perennial grass, with high efficiency in photosynthetic process [43] and [44]. This crop is harvested five times in average before replanting, and in Brazil a 6-year cycle is normally implemented. This crop cycle is often composed by a 12–18 months plant cane cycle, followed by four or more ratoon cycles, and one crop reform period [45,46], and [47].

Sugarcane ratoons are sprouts from the base of cane plants after cutting, or from successive cuttings in ratoon cane [48]. Ratoons are often harvested after 12 months, as displayed in Table 1 [49,50], and [51].

Ratoons have similar growth to the plant cane, diverging most in terms of production efficiency, rooting and sprouting processes [52].

The crop coefficient Kc is the ratio between crop evapotranspiration and the reference evapotranspiration, under optimum growing conditions [53]. Furthermore, in this study, Kc has different values in the case of ratoon cultivation treatment when compared to plant cane, with ratoons Kc values presented in Table 1 [49] and [50].

The sugarcane phenology might be divided into four phases: (1) Emergence/Establishment: the ratoon sprouting and emergence phase; (2) Development/Tillering: the tillering phase, when the sprouted ratoons quickly start tillering; (3) Elongation/Grand Growth: the stalk elongation phase; and (4) Physiological Maturation/Ripening: the maturity phase with intense accumulation of sucrose [46] [49], [52,53], and [54].

The duration of each phase varies depending on climate conditions, varieties and cultural practices [55]. Table 1 also displays the length of each one of the phases.

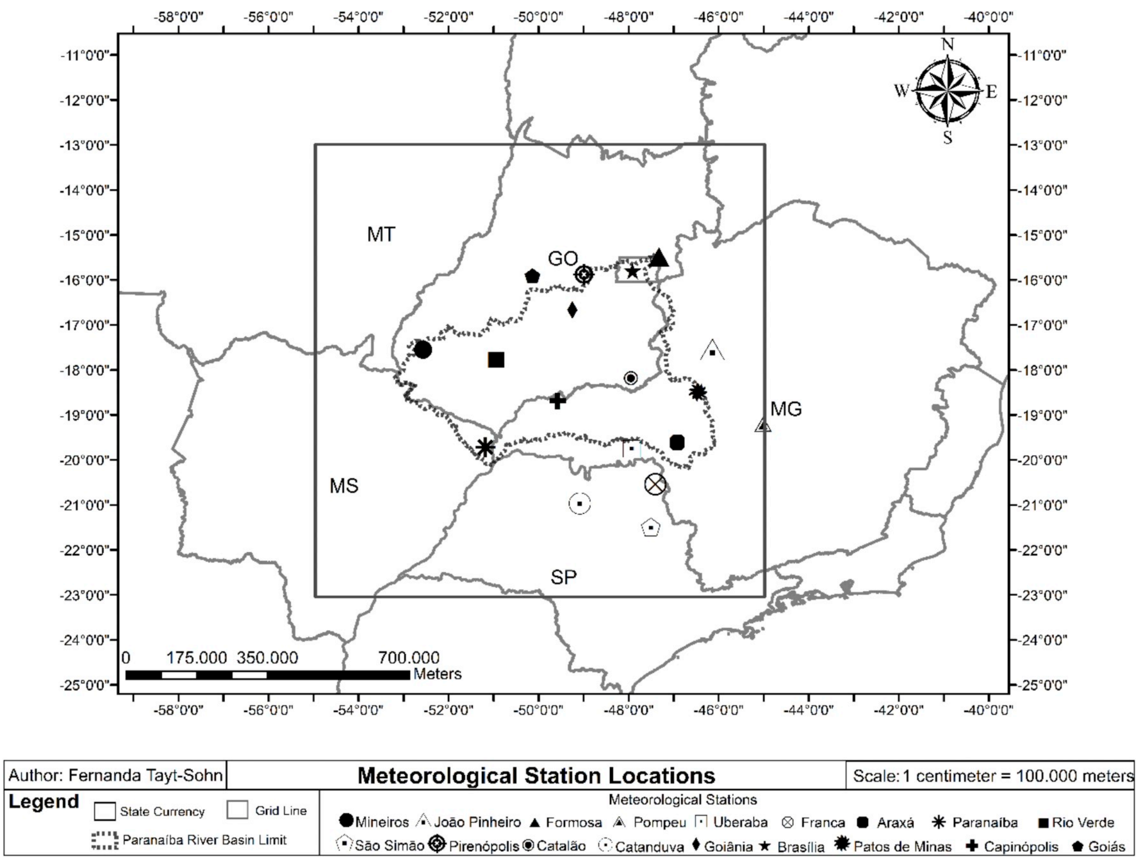

Fig. 1. Map of meteorological station locations used in this research (different marker formats), PRB limits marked in thick black dashed lines. The solid gray lines enclose the study area (between latitudes 23°S and 13°S, and longitudes 55°W and 45°W). Acronyms (GO, MG, MS and SP) represent Brazilian states of: Goiás, Minas Gerais, Mato Grosso do Sul and São Paulo, respectively. Data from Refs. [22] [24] [25], and [33] were used in the elaboration of this map.

Table 1
Sugarcane culture information used as input to the CropWat 8.0. Source: [47], [48] [49], [50] [51], and [52].

Crop	Sugarcane Ratoon
Principal Phenological Periods	(Period 1) Emergence/Establishment (Period 2) Development/Tillering (Period 3) Ellongation/Grand Growth (Period 4) Physiological Maturation/ Ripening
Root System (meters)	100%: 1.5 m
K_c	Initial and Development: 0.4 Half: 1.25 End: 0.75
Duration of vegetative periods (day)	Period 1–Period 2: 30 days (2.59×10^6s) Period 2–Period 3: 60 days (5.18×10^6s) Period 4: 180 days (1.55×10^7s) Period 5: 95 days (8.20×10^6s)

2.3. Climate projections

Monthly means of meteorological variables are also obtained from the numerical integrations of Earth System Model 2G (hereafter ESM2G) and Earth System Model 2M (hereafter ESM2M). Both ESMs are in the IPCC-CMIP5, and were developed at Geophysical Fluid Dynamics Laboratory (GFDL) of the National Oceanic and Atmospheric Administration (NOAA) [56], [57]. Both historical ESM outputs overlap the period of the meteorological station data.

For the evaluation of the projected change, this study also uses the 30-year ESM2G and ESM2M monthly projections driven by the Representative Concentration Pathway 4.5 and 8.5 (henceforth RCP 4.5 and RCP 8.5) as discussed in Refs. [58] and [59], and might be considered moderate and strong forcing paths scenarios, respectively.

The choice of the climate change paths was based on the total radiative forcing and level of CO_2 equivalent concentration by 2100, prioritizing the contrast between them. A near-future 30-year period, from January 2006 to December 2035, is considered in agreement with [14]. The historical integrations and projections are available at Geophysical Fluid Dynamics Laboratory website [60].

According to [56], the ESM2G and ESM2M have the same Atmospheric Model (AM2) and Land Model version 3.0 (LM3.0), which includes dynamic vegetation component. LM3.0 is driven by different scenarios of land use transitions, with four land use categories, and five competing vegetation types, which are reevaluated annually in terms of higher aptitudes of climate and of atmospheric CO_2 concentration [61] and [57].

As stated by Ref. [56], only the oceanic component differs in a relevant way between both ESMs, for instance, ESM2G and ESM2M oceanic models have density [56] and [62], and depth [63] as vertical coordinates, respectively.

Also discussed in Ref. [56], differences between the two ESMs are found in the region of Equatorial Pacific Ocean mode, *El Niño*-Southern Oscillation (hereafter ENSO), with *Niño-3* region (5°N–5°S; 90°W–150°W) being more representative in the ENSO of ESMs' historical integrations, showing ESM2M (ESM2G) stronger (weaker) ENSO in comparison with observations.

2.4. Applied methods

Meteorological variables from ESM2G and ESM2M underwent unit conversion and area selection, as displayed in Fig. 1 (13°S–23°S; 45°W–55°W). As mentioned before, the monthly means over a 30-year

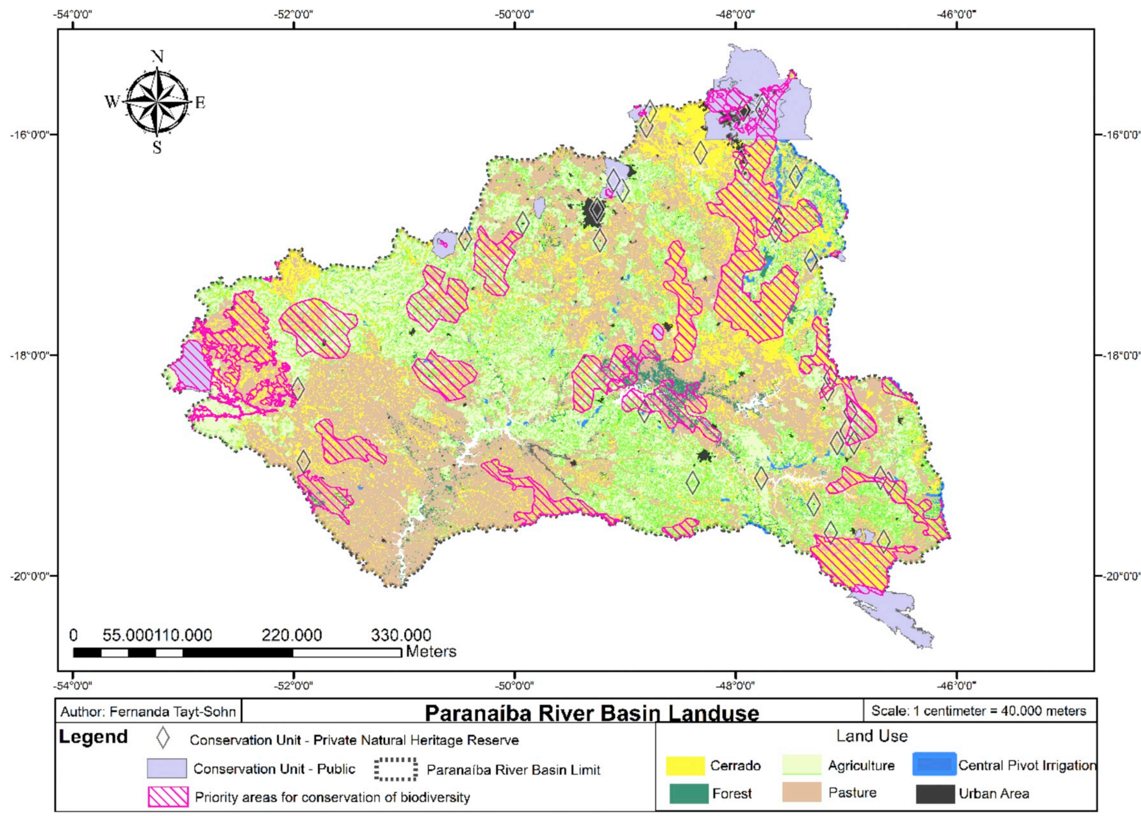

Fig. 2. Land use in PRB (color-shaded areas); priority areas for biodiversity conservation (hatched areas) and Environment Conservation Units (shaded areas in lavender color on the map). The tropical savanna biome knowing as *Cerrado* is represented in yellow. Data from Refs. [23] [24], and [25] were used in the elaboration of this map. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

period generated the monthly climatology used as input to CROPWAT 8.0, developed at the Land and Water Development Division of FAO [64]. Because of the coarse resolution of the ESMs (2.0-degree latitude and 2.5-degree longitude, as described in Ref. [56]), it was necessary to increase resolution to obtain the agroclimatic aptitude maps. To accomplish this, this study applied a simple statistical downscaling method: the Delta Change Approach (DCA). In DCA, change factors (CFs), derived from global climate models, are superimposed over climatological means from observed data [65,66].

Despite the simplicity of this method, in studies of mean climate characteristics the results of the DCA method are equivalent to those from complex statistical downscaling methods [65].

2.4.1. The delta change approach method

The DCA method has been widely used in environmental impact studies (e.g. [67-70]). The DCA methodology applied in this work can be summarized through two basic formulations, as explained in Ref. [69] and given as follows:

$$\overline{CF_{add}} = \left(\overline{V_{sp(monthly)}} - \overline{V_{so(monthly)}}\right) \tag{1}$$

$$\overline{V^{*}_{(monthly)}} = \overline{V_{obs(monthly)}} + \overline{CF_{add}} \tag{2}$$

where CF_{add} is the added change factor, V_{sp} is the projected value from the global model driven by any of the two Representative Concentration Pathways (RCPs); V_{so} is the simulated value in the historical period. All variables are mean values over a 30-year period in the historical and projections periods, as indicated by the "overbar". In Eq. (2), V^* is the projected value of the meteorological variable at the model grid where the station point is located; V_{obs} corresponds to the value of the meteorological variable obtained from station records (observation).

There are some variations in the DCA methodology, but according to [71], DCA, as in Eqs. (1) and (2), is usually employed in the assessment of projected changes of the following variables: wind velocity, solar radiation, and precipitation. In the case of precipitation, Eqs. (1) and (2) are rather applied under dry conditions. However, also according to [71], in the situation that the time interval of the observed data is the same as the climate projections, most of the DCA methods present comparable results.

In order to visualize the change between the observed and projected values, maps were generated containing the change for two main factors which influence the growth of sugarcane: temperature and precipitation [55]. Thereby, the annual mean near-surface air temperature (K) (Fig. 3) and the annual mean precipitation (%) (Fig. 5) were selected.

2.4.2. The CROPWAT model

The CROPWAT model developed by Ref. [73] estimates the crop water requirements and is widely used to assess the need for irrigation, and water deficit [74] [75-77], and [78]. In this study, CROPWAT 8.0 calculates the water deficit, using the Penman-Monteith equation [50], as below:

$$\lambda ET_0 = \left\{[\Delta(R_n - G)] + \rho_a c_p\,[(e_s - e_a)]/r_a\right\} / \left\{(\Delta + \gamma\left(1 + \frac{r_s}{r_a}\right)\right\}, \tag{3}$$

where λ is the latent heat of vaporization of water [J kg^{-1}]; ETo is the reference evapotranspiration [kg m^{-2} s^{-1}]; R_n is the net radiation at the crop surface [W m^{-2}]; G is the soil heat flux density [Wm^{-2}]; e_s is the saturation vapor pressure [Pa]; e_a is the actual vapor pressure [Pa], ($e_s - e_a$) is the vapor pressure deficit of the air [Pa]; ρ_a represents the mean air density at constant pressure [kg m^{-3}]; c_p is the specific heat of the air [J kg^{-1} K^{-1}]; Δ is the slope of the vapor pressure curve [Pa K^{-1}]; γ is the psychrometric constant [Pa K^{-1}]; and r_a *and* r_s are the aerodynamic [s m^{-1}] and the (bulk) surface resistances [s m^{-1}], respectively.

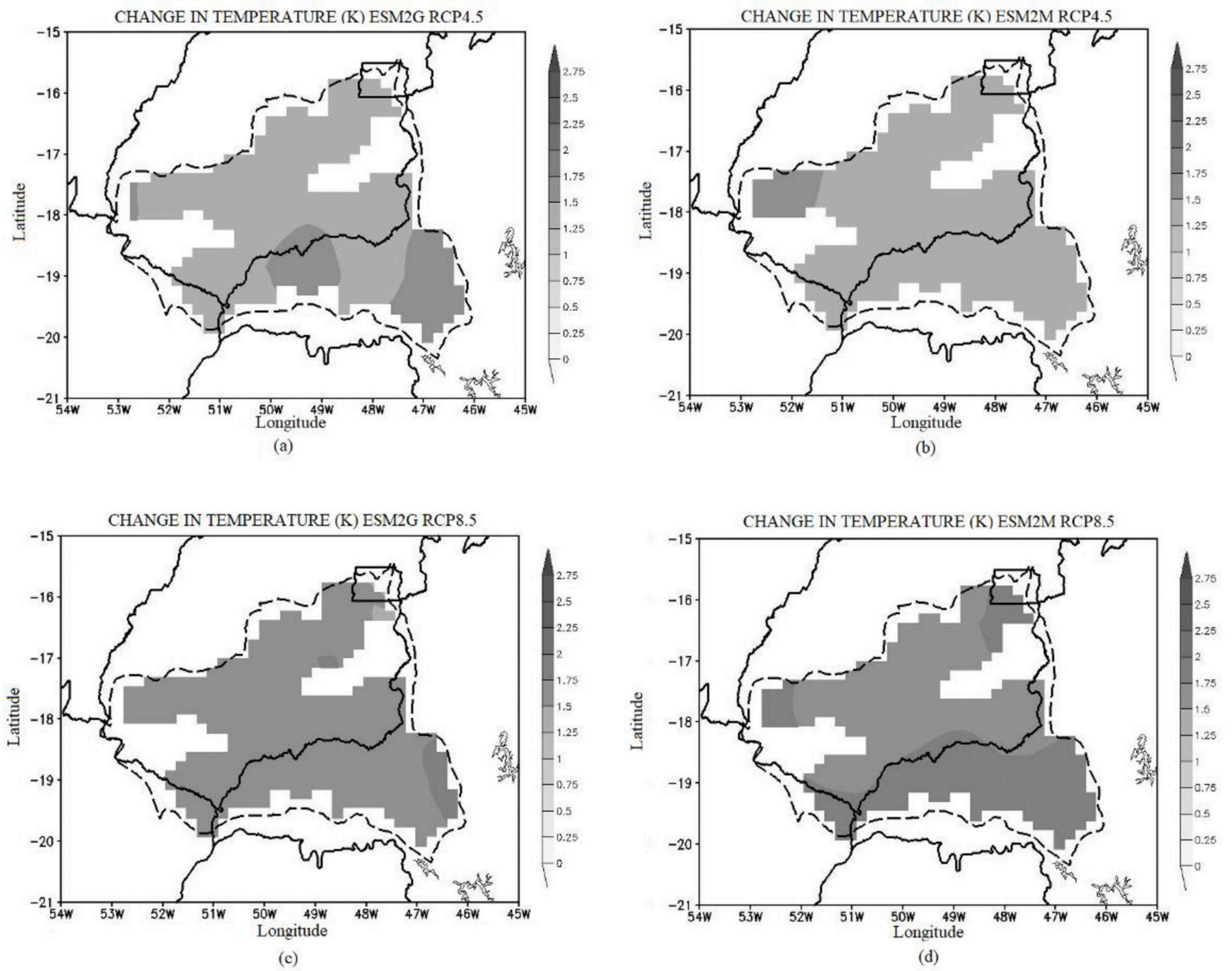

Fig. 3. Change in the projected annual means of the near-surface air temperature from the current climate (observed climatology) values (K), over PRB (dashed line) for: moderate pathway (RCP 4.5) ESM2G (a) and ESM2M (b), and strong pathway (RCP 8.5) ESM2G (c) and ESM2M(d). Values are displayed in grayscale.

2.4.3. Agrometeorological aptitude

The near-surface air temperature values obtained from the ESM2M and ESM2G outputs, the station data climatology, and the results on water deficit from CROPWAT 8.0 were interpolated inside the limits of PRB.

As mentioned earlier in Section 2, the methodology used to establish the agrometeorological aptitude only considers thermal and hydric aptitudes, however applying limits, recommended irrigation practices, such as salvage irrigation, which is often used after each harvesting, with water levels varying from 0.02 to 0.08 m^3/m^2, to ensure sugarcane sprouting [79], and risk levels based on AEZ-Cane methodology [15], as seen in Table 2.

All maps discussed in Subsections 2.4.1 and 2.4.3 were generated on GrADS [19], and were spatially interpolated using Cressman Objective Analysis [18]. The MeteoInfo program [72] was used to process the data, removing all information from outside PRB.

2.4.4. Sugarcane expansion, land use and environmental conservation units

The assessment of the sugarcane expansion in a way that causes less impact to the environment was achieved by the evaluation of the possible threats to environmental conservation units and land uses, both displayed in Fig. 2.

The regulations on environmental conservation units in Brazilian territory are discussed in Ref. [80], and are not directly addressed in this study. For the purpose of this work, only the positioning of the environmental conservation units will be used.

3. Results and discussion

3.1. Thermal and hydric aptitude maps

In Fig. 3 is shown that temperature rises in all scenarios from both ESMs, with the highest change in annual mean near-surface temperature values (~ 1.75–2 K) occurring in the ESM2M driven by the strong pathway (Fig. 3 d), the [81] reported equivalent results to the change in near-surface air temperature under RCP 4.5 with an ensemble of 42 models.

Nevertheless, the thermal aptitude for all scenarios indicates low risk to the sugarcane cultivation over the entire PRB (Fig. 4), meaning that the increase in the near-surface air temperature is not a limiting factor, even in the most adverse scenario (Fig. 3d; 4e). According to [82], the rising in mean global air temperature (between 1.8 and 3.6 K), would be beneficial to sugarcane cultivation.

On the other hand, the projected annual precipitation decreases in almost the entire area of PRB in ESM2G forced by both RCPs (Fig. 5 a-c). In the case of ESM2M, it decreases over the entire area of PRB (Fig. 5 b-d), and impacts the hydric aptitude (Fig. 6 b-e). Comparable results of projected precipitation change were discussed in Ref. [81] to RCP 4.5, with an ensemble of 42 global climate models.

The hydric aptitude has the largest area of medium risk to the

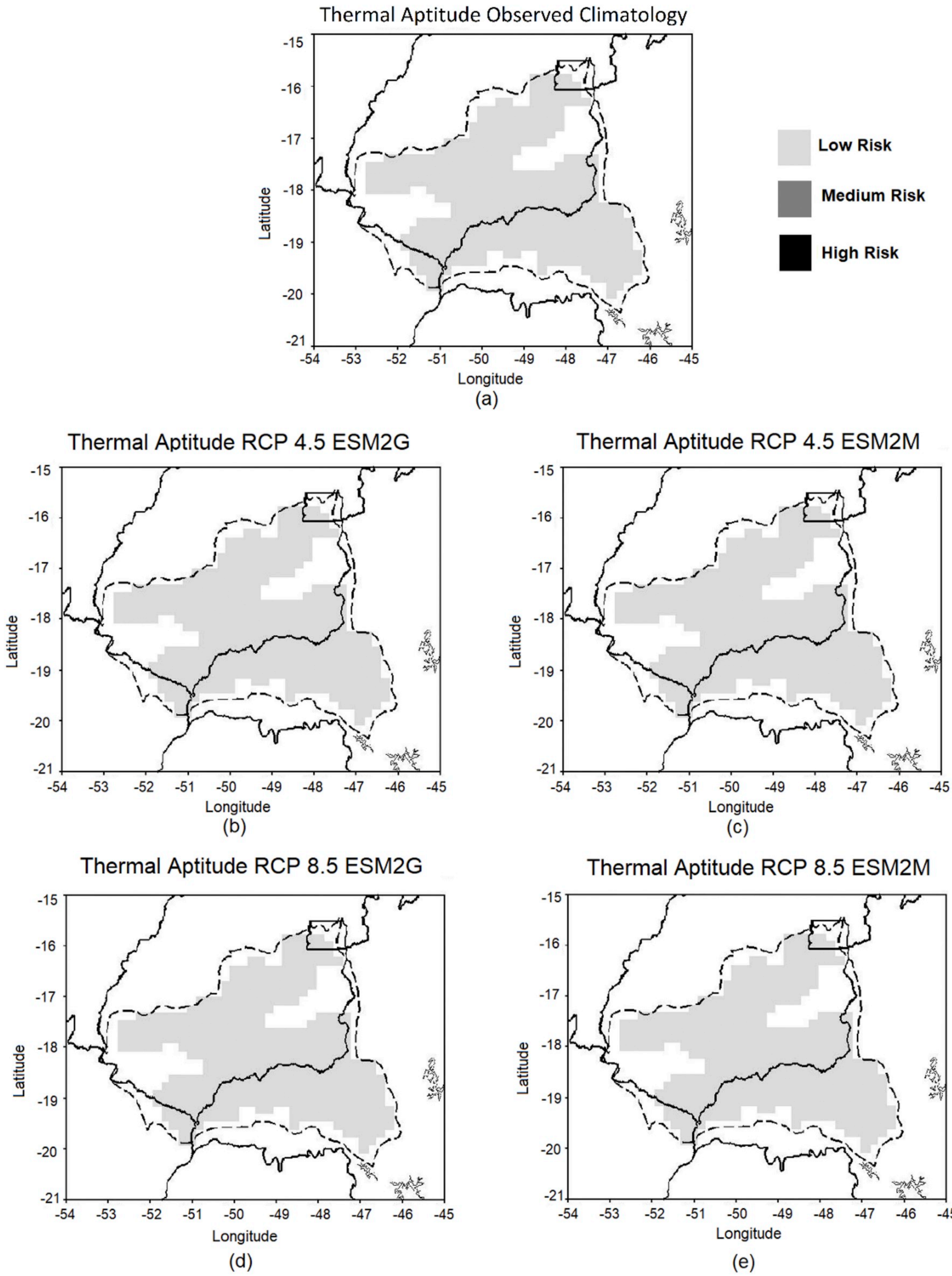

Fig. 4. Sugarcane thermal aptitude for: observed climatology (a), and ESM2G and ESM2M forced with moderate pathway (RCP 4.5) (b) and (c), and strong pathway (RCP 8.5) (d) and (e), over the PRB (dashed line). Low, medium and high risk values are displayed in shaded grayscale.

cultivation of sugarcane, approximately 14.5% of the PRB total area, for the observed climatology from station data, as seen in (Fig. 6 a), wherein salvage irrigation is indicated.

Projections from ESM2G, under RCP 4.5 and RCP 8.5 (Fig. 6b–d), also indicate the necessity of salvage irrigation due to the presence of medium-risk areas, 13.5% and 10% of the PRB area, respectively.

The decrease in the projected precipitation in ESM2G (Fig. 5 a-c) contributed to diminish the water deficit area of medium risk, and to increase the area of high risk in comparison with the observed climatology (Fig. 6 a) for both scenarios (Fig. 6 b-d). Although the water deficit region of medium risk became smaller in the ESM2G-driven projections, the decrease in precipitation impacts less, with the projected precipitation from ESM2G showing reduction from 1.5% to 5%, in RCP 4.5, and 0.5%–5% in RCP 8.5 (Fig. 5 a-c), when compared to the ESM2M projected change, with decrease from 2.5% to 7.5%, in RCP 4.5, and more than 10%, in RCP 8.5 (Fig. 5 b-d). In this study, the

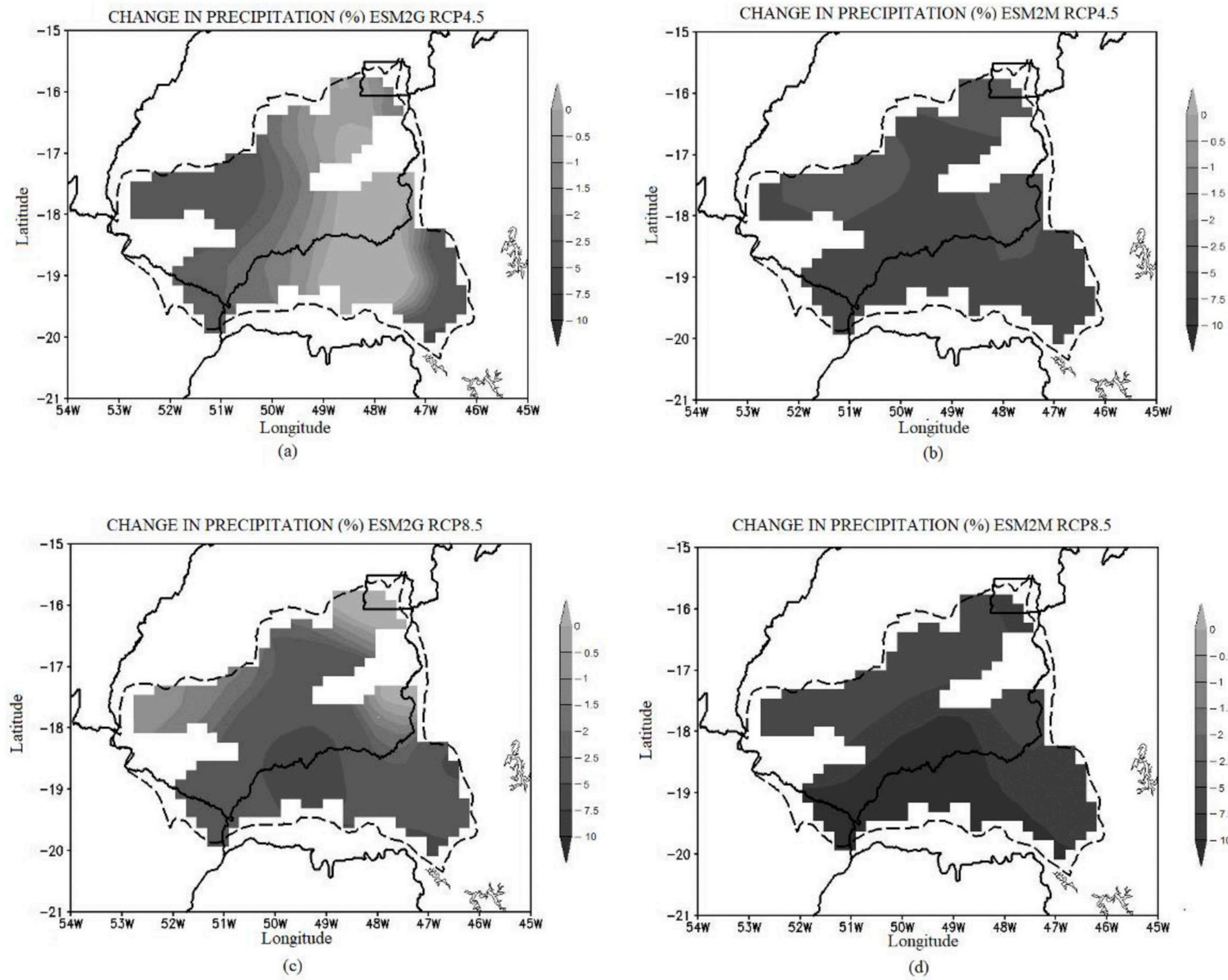

Fig. 5. Change in the projected annual means of the precipitation from the current climate (observed climatology) values (%), over PRB (dashed line) for: moderate pathway (RCP 4.5) ESM2G (a) and ESM2M (b), and strong pathway (RCP 8.5) ESM2G (c) and ESM2M(d). Values are displayed in grayscale.

Table 2
Agrometeorological aptitude methodology based on [15].

Low Risk–Without restraint to cultivation
292.15K < annual mean air temperature;
Water Deficit < 200 mm;
Medium Risk–Salvage irrigation indicated
292.15K < annual mean air temperature;
200 mm < Water Deficit < 400 mm;
High Risk–Intensive irrigation required
292.15K > annual mean air temperature;
Water Deficit > 400 mm;

ESM2M projections exhibit high risk areas over the entire PRB, for both RCP 4.5 and RCP 8.5 (Fig. 6 c-e).

Despite ESM2G projections driven by RCP4.5 and RCP8.5 have areas with slightly increase in precipitation (Fig. 5 a-c), the projected regions of high risk do not show any decrease in area (Fig. 6 b-d), with the values of water deficit still above the medium risk threshold (> 400 mm, as indicated in Table 2) (not shown).

Differences seen in the climate projections at the station sites might be explained by the oceanic forcing from both ESMs, leading to distinctive ENSO responses as discussed in Ref. [56]. ESM2M has the strongest ENSO in the historical integration, and projects more pessimistic scenarios, with greater water deficit (Fig. 6 c-e), whereupon all the analyzed area of PRB requires intensive irrigation (> 400 mm per cycle of sugarcane), according to Table 2.

3.2. Evaluation of the sugarcane expansion in PRB

The southwestern part of the basin shows the lowest risk to the cultivation of sugarcane (Fig. 6a–e), with fewer environmental conservation units, as shown in Fig. 2. Southwestern PRB is mainly covered with pasture (Fig. 2) for approximately 10.7 billion m^2 (1.07 million ha). Additionally, this region is one of the areas with the lowest water deficit under different ESMs scenarios (not shown).

From Ref. [14], an expansion of 8 billion m^2 (0.8 million ha) in sugarcane cultivated area is estimated in all Brazilian territory until 2026. If all the sugarcane expansion occurred in PRB, the southwestern side of PRB would have the pastureland replaced with sugarcane cultivated area, without taking new lands and threatening environmental conservation units with the expansion.

Another condition to sugarcane expansion that cause less impacts to the environment is through the reallocation of cattle herd towards degraded pasturelands. Considering assessments of different levels of degraded pasturelands over the state of Goiás approximately 50 billion m^2 (~5 million ha) [83], and the estimations of 46 billion m^2 (~4.6 million ha) undergoing degradation in the state of Minas Gerais [84], and the productivity percentage in degraded pasturelands (32%–34%) [85], it would be possible to reallocate the cattle herd towards degraded pasturelands and expand the sugarcane cultivated area without requiring new lands [85-87].

In that regard, Low Carbon Agriculture Plan encourages the

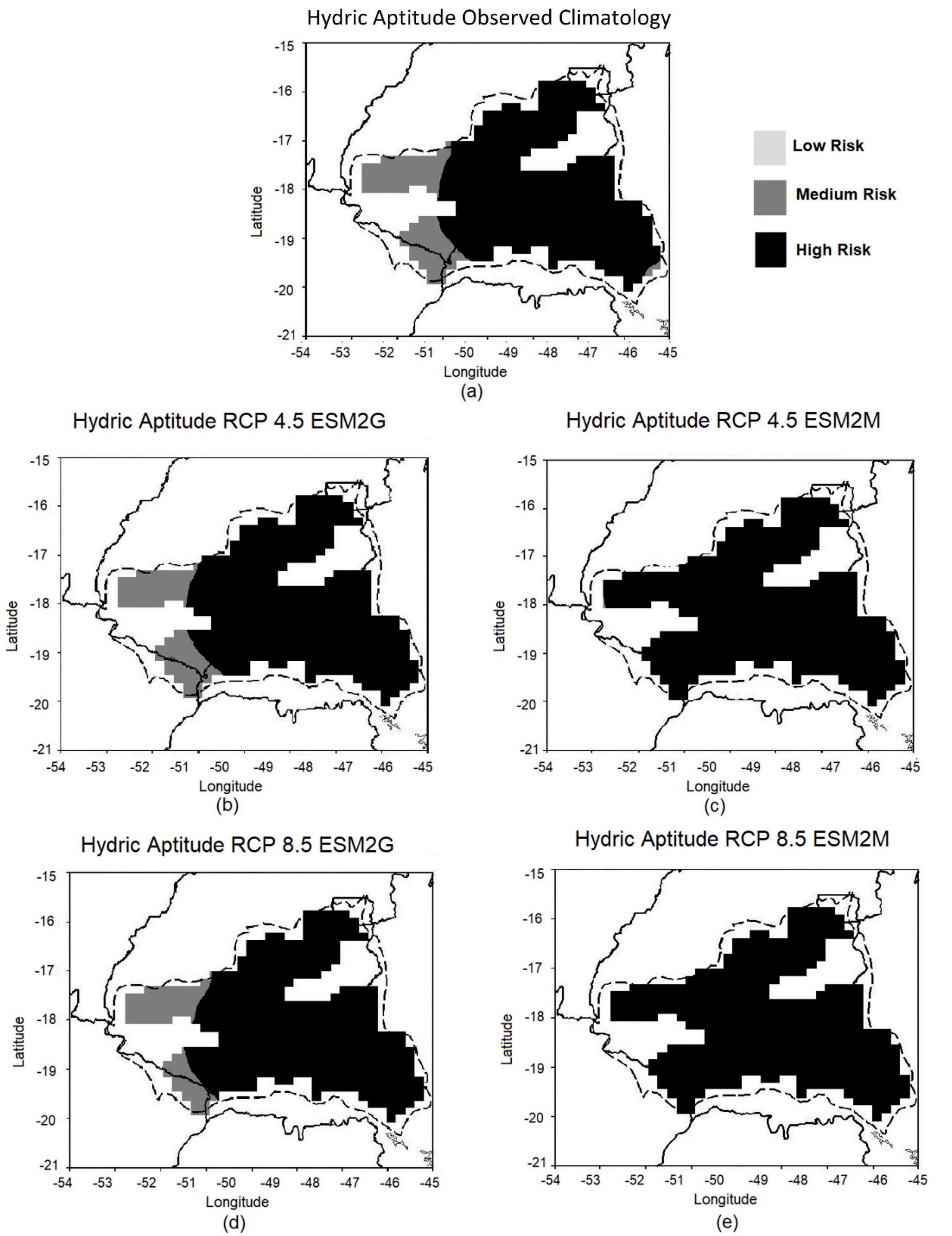

Fig. 6. Sugarcane hydric aptitude for: observed climatology (a), and ESM2G and ESM2M forced with moderate pathway (RCP 4.5) (b) and (c), and strong pathway (RCP 8.5) (d) and (e), over the PRB (dashed line). Low, medium and high risk values are displayed in shaded grayscale.

recovery of degraded pasturelands through different government incentives [88]. Furthermore [89], highlights that changing pasture into sugarcane cultivated area causes a cooling effect over the region. Consequently, sugarcane expansion is recommended to occur in the southwestern part of PRB.

As also discussed in Ref. [75], the southwestern PRB exhibits quantitative indicator of surface water resources to sugarcane cultivation, and the same study emphasized that the yield losses would be reduced, if irrigation were implemented. Taking into consideration the water demands associated with water security and irrigation costs [75], reinforced that the water footprint indicator is favorable to the southwestern PRB as an expansion area for sugarcane cultivation.

The AEZ-Cane results [15] and other studies [75] [85], [86], corroborate the southwest region of PRB as a suitable region for sugarcane expansion.

Although the ESM2M RCP4.5 and RCP8.5 projections have presented high risk in the entire river basin (Fig. 6 b-d), with intensive irrigation (> 400 mm per cycle of sugarcane, as shown in Table 2), it would be possible to endorse the cultivation in the southwestern PRB, since this region is one of the areas with the lowest water deficit values.

4. Conclusions

Using observational data and two IPCC-CMIP5 projections, this research supports the sugarcane expansion to the region with the lowest impact to the environment, the southwestern PRB, showing results similar to those reported by Refs. [15] [75] [85], and [86], despite the differences in the climate projections used in the current study.

In this study, projections from ESM2G and ESM2M indicate high-level risk of water deficit over PRB, yet projections driven by ESM2G point to medium-level risk in the western part of PRB, which might be associated with the two ESMs' distinctive ocean forcing responses.

The assessment from agroclimatic aptitude maps indicate the southwest of PRB as the best location for sugarcane cultivation expansion. However, in the case of ESM2M-driven projections, only with intensive irrigation (> 400 mm per cycle) would be possible to cultivate sugarcane in the southwest region of PRB.

All that considered, if the all projected expansion of sugarcane cultivated area for all Brazil occur inside PRB, the pastureland of its southwest region would be enough to support the expansion, with around 65% of its extent replaced with sugarcane crop. Also, the cattle herd would be reallocated toward degraded pasturelands, without requiring new lands.

Ultimately, this methodology could be used in other prospected expansion regions located between North and Northeast Brazil, and applied to other crop models using daily climate data, as they might produce more elaborated results.

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